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BRIEF (FOR REPORTS OF MORE THAN ONE PAGE, ENTER C	CAREFUL SUMMARY)
Ref: (a) CINCNELM REP FXFT IR (b) ATI IR 9549-57 dtd 12	

# INFORMATION REPORT

OFFICE OF NAVAL INTELLIGENCE

OPNAV FORM 3820-2 (CNFG) (REV. 11-56)

SERIAL NO. F13-58 DATE OF REPORT 16 January 1958 **EVALUATION** REQUEST NO.

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PAGES

(OMI ONLY) A. F. JOFFE, MALSLEITER THERMOELEMENTE, Akademie Verlag-Berlin (Original German)

(ONI OLLY) English Translation of Sections of Chapter II of enclosure kx 1.

1. Enclosure (1) is a German Language edition of a book on semi-conductor thermal elements which was published in Russian language edition in 1956. Another copy of this book was previously forwarded as enclosure (1) to reference (a). Enclosure (2) is an English translation of Chapter II (THERMOELECTRIC GENERATORS) at enclosure (1).

It was announced in IZOBRETATEL STOVO SSR MOSKA USSR as quoted in reference (b) that:

"Researchers of the Central Scientific Boiler Turbine Research Institute Im. I. POLZUNOV (TSENTRAL'NYY NAUCHNO-ISSLEDOVATEL'SKIY KOTLOTURBINNY INSTITUTE IM. I POLZUNOVA) together with researchers of the LENINGRAD Semi conductor Institute of the USSR Academy of Science designed a new energy installation and called it "Thermoelectrical Generator". It is based on the idea of academician A. F. IOFFE. Semiconductor elements for a theroelectrical battery are the secret of the new "Miraculous furnace". Its inner surface is lined with such elements. They are cooled with water and thus generate an electric current of a tension suitable for illuminating purposes. The power of this first installation equals one KW. would suffice to illuminate a 25 room house with 40W bulbs. It can also heat up 40 pails of water in one hour. The new device may prove its importance in areas that are far away from energy sources.

THIS REPORT CONTAINS UNPROCESSED INFORMATION. PLANS AND/OR POLICIES SHOULD NOT BE EVOLVED OR MODIFIED SOLELY ON THE BASIS OF THIS REPORT.

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#### INFORMATION REPORT

OPNAV FORM 3820-2 (C) (CNFG) (REV. 11-56)

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FROM

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3. In an article published in a recent edition of TEKNIKA MOLODEZHI, Professor JOFFE pointed out that it is possible to convert <u>nuclear</u> and <u>solar</u> energy into electricity. He emphasized that the <u>size</u> of the equipment which is used to transfer nuclear energy into electricity could be greatly reduced in this way.



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Soviet Zone Germany publisher is the source of enclosure (1).

Paragraph 2 is quoted from an ATI IR which was received on lateral distribution from USAFE.

Paragraph 3 is quoted from NUCLEUS, a West German Weekly Newsletter.

# Preparing Officer's Comment:

The fact that JOFFE is we working with the Central Boiler Institute POLZUNOV in LENINGRAD which has a large scientific staff which are known to do research on naval boilers and turbines and their control may indicate Soviet Naval interest in his work.

The mention by JOFFE of the application of THERMO ELECTRIC Generators to nuclear power is not surprizing.

It is of interest that JOFFE states (see page 33 of enclosure 1) "It is thus not impossible with the of semiconductors to obtain efficiencies of 1-15 percent or indeed more. In the literature values of 3.3 to 7 percent are given."

The VACUUM THERMOELEMENT discussed on page 56 of enclosure (1) seems to be identical with the development recently given much publicity by the U.S. General Electric Co.

This report is believed to be of interest to BuShips (Code 560P) ONR (Code 469) and OPO22F2E.

An English translation of this item may be found on page 21 of enclosure (1).

Prepared:

S&T UNIT

Forwarded:

A. R. CZERWONKY



INFORMATION REPORT ENCLOSURE (2) to IR F13-58 dtd 16 Jan 58

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UNCLASSIFIED CINCNELM REP FRANKFURT, APO 757 F13 58 16 Jan 1953

SEMICONDUCTOR THERMOELEMENTS by A. F. Joffe (English Translation)

ChapterXX II.

THERWOELECTRIC GENERATORS.

# 6. - Energetic Bases for Thermoelectric Batteries.

We consider a thermocouple (Fig. 1) consisting of a p-type conductor (1) and a n-type conductor (2) joined by a piece of metal (3). A load resistor  $\mathcal{K}$  taking up the electric energy produced by the **xx** thermocouple is connected to the cold ends. When V is the potential difference at the cold ends, the power produced by the thermocouple is and the amperage is  $\mathcal{I} = \mathcal{K}$ .

The thermoelectric force which  $\dot{x}$  our case is equal to the sum of the thermoelectric force of the two branches is designated by  $\propto$ 

$$\alpha = \alpha_1 + \alpha_2$$

The hot soldered joints joined by the piece of metal have the temperature  $\sqrt{\phantom{a}}$ , the thermal energy being supplied by a source having a high temperature. The cold ends have the temperature  $\sqrt{\phantom{a}}$  that is a little higher than the ambient temperature or the temperature of a special cooling device.

The internal resistances of the two branches we designate by  $\Gamma_i$  and  $\Gamma_{Z_i}$ , their thermal conductivities by  $K_i$  and  $K_{Z_i}$ . Naming the **xparkigi** specific resistance  $\rho_i$ , the specific thermal conductivity  $X_i$  and assumin, equal lengths  $Q_i$  for the two branches, furthermore denoting the cross-sectional areas by  $A_i$  and  $A_{Z_i}$ , we have:

$$r = r_1 + r_2 = \left(\frac{f_1}{A_1} + \frac{f_2}{A_2}\right) l$$
 $K = K_1 + K_2 = \left(\frac{\chi}{A_1} + \frac{\chi}{A_2}\right) \frac{1}{k}$ 

The Peltier heat given off and/or taken up at the ends of the thermocouple can be calculated with the help of the general laws of thermoelectricity, just as can the thomson heat produced or consumed within the bars. Also, we compute the heat transferred by conduction from the hot ends to the cold ends and the joule heat produced by the current.

Then we can determine the useful electric energy supplied by the thermocouple. All forms of energy are referred to a second and the power is expressed in terms of watt. The purely thermal magnitudes are expressed in terms of the same units, e.g., the specific thermal conductivity  $\times$  in terms of watt/degree centimeter rather than in terms of calories/degree centimeter second:  $\times$ 

\* See page 26. ENCL(2)

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The thermal energy taken up at the hot ends per second is:

$$Q_{i} = \alpha_{i} I T$$

The power delivered by the cold ends is:

The Thomson heat produced in each bear is according to

$$Q = \pm \int \frac{dx}{dT} I dT$$

When  $\alpha$  has equal values at both ends, then  $\varphi = 0$ 

The energy time conveyed by the heat flow in the two bars from the hot ends to the cold ends per second is

$$Q_{ij} = K(T_i - T_o)$$

The power produced in the two bars by the current is

$$Q_J = J^2 R$$

The useful power supplied by the thermocouple is

$$W = I^2 R$$

The current is

$$I = \frac{\langle (T, -T_0) \rangle}{R + r}$$

With the notation

$$\frac{R}{r} = m, \quad we obtain: \quad W = \alpha^{2}(T_{1} - T_{0}) \frac{1}{r(m+1)^{2}}$$

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we obtain 
$$Q = \chi^2 T_1 \left( T_1 - T_0 \right) \frac{1}{r(m+1)}$$

$$W = \chi^2 \left( T_1 - T_0 \right)^2 \frac{m}{r(m+1)^2}$$

For the time being we neglect the Thomson heat which is a small with reference to the sother magnitudes and therefore have written  $\alpha = \alpha = \infty$ 

When  $\alpha$   $\neq \alpha_o$ ,  $\alpha$  in the equation for the efficiency must be substituted by the mean value of the two ends  $\alpha = (\alpha_i + \alpha_o) \frac{1}{2}$  when the Thomson heat is taken into ENNEW consideration.

Of the Joule heat  $\mathcal{I}^{\mathcal{Z}}$  produced within the thermocouple one half is transferred to the hot soldered joints and is refunded to the source. There remains a power  $\frac{\mathcal{I}}{2}\mathcal{I}^{\mathcal{Z}}$  that travels to the cold soldered joint.

The efficiency f is defined as the ratio of the useful electric energy  $\int_{-\infty}^{\infty} \mathcal{K}$  that can be consumed in the extern external circuit to the energy supplied by the source of heat. It is energy is composed of the Peltier heat  $Q_{ij}$ , the quantity of heat  $Q_{ij}$  that is conveyed to the cold soldered joints by conduction, minus the electric energy  $\frac{1}{2}\int_{-\infty}^{\infty} \mathcal{K}$  that is refunded to the source of heat.

Hence we have

$$\eta = \frac{W}{Q_{1} + Q_{W} - \frac{1}{2} I^{2} r}$$

$$= \frac{\chi^{2} (T_{1} - T_{0})^{2} \frac{1}{r} \cdot \frac{M}{(M+1)^{2}}}{\chi^{2} T_{1} (T_{1} - T_{0})^{2} \frac{1}{r} (M+1)^{2}}$$

$$= \frac{\chi^{2} (T_{1} - T_{0})^{2} \frac{1}{r} \cdot \frac{M}{(M+1)} + K(T_{1} - T_{0})^{2} \frac{1}{r} \frac{\chi^{2} (T_{1} - T_{0})^{2}}{r (M+1)^{2}}$$

$$= \frac{M}{M + 1}$$

$$= \frac{T_{1} - T_{0}}{T_{1}} \cdot \frac{M}{r} + \frac{K_{V} M_{1} + 1}{T_{1}} \cdot \frac{T_{1} - T_{0}}{2 T_{1}} \cdot \frac{1}{M + 1}$$

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Consequently, the efficiency of a thermocouple is completely determined by

- a) the temperatures of the hot and cold soldered joints,
- b) the magnitude  $\sqrt{\alpha}^2$  which depends on the properties of the materials out of which the thermocouple is made. This magnitude we denote by  $\frac{1}{2}$  so that

$$Z = \frac{\alpha^2}{Kr}$$

c) - the ratio 
$$v_0 = R_v$$

In order that for given values of and any ratio the efficiency becomes a high as possible the cross-sectional areas a, and any ratio the efficiency becomes a to be the most faborable, i.e., that for the given values of and the product Kr becomes as small as possible.

In order to find the minimum value of Kr we differentiate

$$Kr = (\chi A_1 + \chi_2 A_2) \left( \frac{\beta_1}{A_1} + \frac{\beta_2}{A_2} \right) = \chi_1 \rho_1 + \chi_2 \rho_2 + \chi_2 \rho_2 \frac{A_2}{A_2} + \chi_2 \rho_1 \frac{A_2}{A_2}$$

with respect to // and equate the term thus obtained to zero. We find

$$\frac{P_1}{X} \cdot \frac{\chi_2}{P_2} = \left(\frac{A_1}{A_2}\right)^2$$

Upon this selection of  $\frac{A_{i}}{A_{i}}$  there is

there is
$$K_{V} = \left(\sqrt{\chi_{1} \rho_{1}} + \sqrt{\chi_{2} \rho_{2}}\right)^{2}$$

$$Z = \frac{\alpha^2}{K_V} = \frac{\alpha^2}{\left(\sqrt{x_i \rho_i} + \sqrt{x_2 \rho_2}\right)^2}$$

In this term there are only contained the properties of the materials of the two branches of the thermocouple; but not their size.

Now we determine the ratio  $\frac{R}{V} = \mathcal{M}$  most favorable from the viewpoint of efficiency. If

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we want maximum power, this demand - as in an any other source of current - leads to the condition R=r or m=/ , and we have

the maximum efficiency is obtained, however, when we put  $\frac{\partial \eta}{\partial u} = 0$ ; after some elementary computation we find  $\frac{\partial \eta}{\partial u} = 0$ 

$$\left(\frac{R}{r}\right)_{opc} \stackrel{\text{def}}{=} M = \sqrt{1 + \frac{1}{2} Z(T_1 + T_0)}$$

wherein  $Z(T_i \not= T_o)$  and M are dimensionless numbers.

By introducing this optimum value of M = M into the term for the efficiency were obtain

$$\eta = \frac{T_{i} - T_{o}}{T_{i}} \frac{M - I}{M + \frac{T_{o}}{T_{i}}}$$

wherein the first factor represents the thermodynamic efficiency of a reversible machine, while the second factor indicates to what extent this efficiency is diminished by the irreversible losses caused by heat conduction and the Joule heat which are contained in the expression for  $\mathbb{Z}$ 

The greater  $\mathcal{M}$  is than unity, and hence the greater and  $\mathcal{Z}$  and  $\mathcal{T}_1 + \mathcal{T}_2$  the lesser will be this diminution of the efficiency. Consequently, by increasing the temperature  $\mathcal{T}_2$  of the hot soldered joint  $\mathcal{T}_2$  is increased not only because of the greater efficiency  $(\mathcal{T}_1 - \mathcal{T}_2 / \mathcal{T}_1)$  of the reversible machine, but also by the simultaneous increase of  $\mathcal{M}_2$  with a given value of  $\mathcal{Z}_2$ .

This formula also indicates clearly that only one condition must be met by the material mout of which the thermocouple is made in order that maximum efficiency be attained: the maximum possible value of Z which is compatible with the maximum temperature I, of the source of heat must be attained or, in other words: the maximum value of the product  $Z(I, I, I_0)$  that is feasible for the given material.

If in the term for  $\eta$  we had meglected  $\frac{1}{2} I^2$  against  $Q_1 + Q_{\omega}$ , we would have obtained:

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$$M' = \sqrt{1 + T_1 z}$$
 $J = \frac{T_1 - T_0}{T_1} \frac{M' - 1}{M' + 1}$ 

The value  $\eta'$  is almost identical with  $\eta$ , provided  $\eta$  is small. For instance, for  $T_1 = 600^{\circ} K$ ,  $T_2 = 300^{\circ} K$  and  $Z = 2 \times 10^{-3} We have <math>M = 1.38$ , M' = 1.48,  $\eta = 0.101$ 

The dependence of  $\eta$  and M on the product  $\frac{1}{2}(T, +T_0)$  is plotted in Figs. 2 and 3 and computed in Table 1 for  $T_1 = 600\%$ ,  $T_0 = 300\%$ , hence,  $(T_1 - T_0)/T_1 = 0.5$  Fig. 4 show the efficiency  $\eta$  (per cent) as a function of Z and T. As

Exponential functions of  $\phi$  and  $\phi$  can be used for a rapid though less accurate estimate of the efficiency of a thermocouple. For  $\frac{1}{10} = 300 \, \text{kthere}$  holds:

In the subsequent & table these values are compared with the precise values

within the interval  $10^{-3}$  2 <  $4x_{\rm and}^{-3}$   $500 \le T \le 1000^{\circ}$ K (last column in terms of percent). The following formula

can be applied with a maximum error of 15 per cent within the narrow limits 500 < T, < 800°k and  $/.5.10^{-3} < 2 < 4.10^{-3}$ 

# 7. Materials for semiconductive thermocouples.

We shall now deal with the materials that are most favorable for thermocouples.

First of all it must be stated that because of their relatively karraxxx large value of semiconductors have decisive advantages over metals. For most metals we have XX/D-/D/KThe ratio of electric x conductiveity V = D to the thermal conductivity X in all metals is close to the theoretical value derived from quantum mechanics

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X = T2 (E)2T = 2.44.10-8T (Wiedemann-Franz Law)

For a mean temperature of  $T = 500^{\circ}$ K there is

and for  $T_s = 700^{\circ}$  K,  $T_o = 300^{\circ}$  K we obtain

$$\eta = 8.5 \times 10^{-4} = 0.085 \%$$

For the most favorable part pair of metals, bismuth and antimony, were have

$$\alpha = 50 \times 10^{-6}, \chi p = 9 \times 10^{-6}, z = 2.8 \times 10^{-4} T, < 500^{\circ} K, T_0 = 300^{\circ} K, \eta = 1.4\%$$

In m numerous semiconductors Z can attain or even exceed the order of magnitude of  $10^{-3}$ . Then  $\beta$  becomes almost equal to 10 percent. Also, there exist semiconductors with a high m melting temperature permitting high values of 77. It is not impossible, therefore, to & attain efficiencies of 10 ..... 15 percent or better with the E help of semiconductors. Values of 7 ranging from 3.3 to 7 percent and stated in the literature.

The higher is the value of  $Z = \frac{\alpha}{2} / \rho$  of the individual branches of the thermocouple, the greater will be

$$Z = \frac{\left(\alpha_1 + \alpha_2\right)^2}{\left(\sqrt{\chi_1 \rho} + \sqrt{\chi_2 \rho_2}\right)^2}$$

by which is defined the efficiency of the whole thermocouple. It is not possible, however, to state the interrelation between the value Z of the whole thermocouple and the Z, and  $Z_2$  of the two krawks branches in a general form. In some cases we have for  $Z_1 = Z_2$ simply  $z=z_1=z_2$ ; for  $\sqrt[3]{-2}$  there is  $z=\frac{1}{4}(z_1+z_2)+\frac{1}{2}\sqrt{z_1}z_2$ . If, as for the best semiconductive materials, (see below) one has  $\alpha_{1} = \alpha_{2} = 172 \mu V/o_{K}$ , there holds

$$Z = \frac{4}{\left(\frac{1}{\sqrt{Z_1}} + \frac{1}{\sqrt{Z_2}}\right)} = \frac{4Z_1Z_2}{\left(\sqrt{Z_1} + \sqrt{Z_2}\right)^2}$$

With the help of Eg. (21) the correlation between  $\propto$  and  $\mathcal{T} = \int_{\mathcal{T}} \operatorname{can} \operatorname{be} \operatorname{determined} \operatorname{in} \operatorname{semiconductors}$ . A linear relation between  $\propto$  and  $\log \mathcal{T} = \operatorname{can} \operatorname{be} \operatorname{determined} \operatorname{in} \operatorname{semiconductors}$ . temperature and the assumption that the mobility remains virtually unchanged in case the concentration is changed:  $\alpha = C - 86 \times 10^{-6} / \text{oge} = C - 2 \times 10^{-4} / \text{oge} = C$ 

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The value of C depends on the temperature T, the mobility and the character of the chemical bond of the semiconductor.

On the other hand  $\nabla$  is related to  $\times$ . The thermal conductivity  $\times$  of a semiconductor is composed of the thermal conductvity of the electrons  $\times_{\mathcal{O}_I}$  and the thermal conductivity of the thermal oscillations and waves (they are designated as the thermal conductivity of the phonons  $\times_{\mathcal{F}^h}$ ):

 $\chi = \chi_{e_1} + \chi_{gh}$ 

The first of these magnitudes is correlated to the electric manning conductivity by the law of WIEDEMANN - FRANZ. Yet, only for very high electron concentrations >2.5 × /o combined in case of degeneration is the factor of proportionality identical with the value that holds for metals

 $\frac{\chi_{el}}{\sigma} = \frac{\pi^2}{3} \left(\frac{K}{E}\right)^2 T$ 

With lesser concentrations as they usually hold in semiconductors we have

$$\frac{\chi_{el}}{\sigma} = \frac{\chi_{el}}{\sqrt{\kappa}} = \frac{\chi_{el}}{\sqrt{\kappa}} = 1.48.10^{-8} \frac{T V^2}{\kappa}$$

For room temperature T = 2930K we hence have

In other words: a conductivity of 1,000 ohm cm is equivalent to a thermal conductivity of 4.35 x 10<sup>-3</sup> who cm or 1.04 x 10<sup>-3</sup> calle cm sec.

Fig. 5 in which are plotted the results of measurements **ithrates** illustrates formulae (36), (3?) and (38) for a semiconductor whose **exercise** conductivity has been changed by varying the electron concentration. (Sec. German or of the content of the content or o

For  $\sigma < 2500$  har can the electrons are not yet degenerated. The  $\times_{e_1} = 4.5 \times 10^{-6} \sigma$  Beyond  $\sigma = 4000$  har can the electrons are rather strongly degenerated, and in this region  $\times_{e_1}$  gradually approaches the value  $\times_{e_1} = 7.3 \times 10^{-6} \sigma$ 

The law of WIEDEMANN - FRANZ describes well the correlation between the thermal conductivity  $\chi_{e/}$  and the electric conductivity  $\mathcal{T}$  only for such semiconstants in which

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the carriers uniformely are of the same sign. If both kinds of carriers are present simultaneously, a steady flow of carriers is possible in the direction of the temperature gradient and a strong increase in the thermal conductivity  $\chi_{e/}$  occurs.

In analogy to diffusion and thermal conductivity of gases the phonon's share in the thermal game's conductivity  $\chi_{\rho_k}$  is described by

$$\chi_{ph} = \frac{1}{3} c N \lambda$$

wherein  ${\bf C}$  is the specific heat (Joule per degree and cubic centimeter),  ${\bf W}$  is the sound velocity (centimeters per second) and  ${\bf A}$  is the mean free path of the phonons (centimeter).

In most semiconductors these values are within the following limits: 
$$1.2 \le c \le 1.6$$
,  $2.10 \le c \le 5.10 \le and$   $10 \le \frac{1}{3} \le c \le 3.10  

A semiconductor's thermal conductivity  $\lambda_{Ph}$  also depends on the mobility u of the electrons and, hence, on the electric conductivity, as the mobility can be expressed in terms of the mean free path  $\tilde{\chi}$  of the electrons.

A theoretical xxx treatment of the dependence of thermal and electrical conductivities on temperature is man omitted. See original German.

The interrelation between thermal conductivity and mobility, which is of very great significance m for thermoelectric applications, has not yet been studied enough. It can only be stated that condictions are more favorable in heavy elements than in light elements.

The thermal conductivity of a thermocouple is of great significance not only for the efficiency but also with regard to the size of thermoelectric batteries and the design of the thermodynamic installations by which heat is conveyed to the hot soldered joints and carried away from the cold soldered joints.

In order that maximum efficiency is attained in a battery of a given composition the temperature T, of the hot soldered joint must be maximized and the temperature T of the cold soldered joint must be minimized. By this requirement is determined the temperature difference T - T. The smaller is the thermal conductivity  $\nearrow$ , the shorter can be the thermocouple, i.e., its length ?.

Transfer rate 7,
The heat-fla density g (defined as the energy passing through a cross section of 2 square centimeter per second) flowing through the thermocouple is described by

$$9 = \chi \frac{T_1 - T_0}{l}$$

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A definite value of  $\mathscr G$  can be ensured by appropriate selection of  $\mathscr L$  and -conversely-with a given heat-flux density the length  $\mathscr L$  of the elements of the battery is given by the thermal conductivity  $\times$  .

In customary thermocouples with an efficiency not in excess of 10 per cent the majority of the heat produced by the source is passed to the cold soldered joints by heat conduction. The power required of the source hence is primarily determined by the power of the heat flow that is conveyed through the two branches of the thermocouple. The electric power that can be generated by the thermo- battery can be described by  $\mathcal{P}(\mathcal{Q}_{\omega})$  wherein  $\mathcal{Q}_{\omega} = \mathcal{P}(\mathcal{A})$  is the cross-sectional area of the battery):

The XMARK power generated by 1 cubic centimeter of the battery (specific power) is:

$$-\omega = \frac{\omega}{5 \cdot \ell} = \eta \chi(T, -T_0) \frac{1}{\ell_0^2}$$

or, with a given heat flow &:

The smaller is the them thermal conductivity, the shorter can be the thermocouple in order that a definite temperature difference is set up; or, the greater must be the heat flux density with a given W. With decreasing length 2 the specific power increases as  $1/p^2$  and the heat-flux density as  $1/p^2$ .

Finally, the thermal conductivity also is the decisive factor in determining the stress and deformations occurring in the battery in case of non-uniform heating.

We denote the linear expansion coefficient by p. Because of the temperature difference  $T_1$  -  $T_0$  between the hot and the cold ends the linear sizes which were equal upon manufacture will change by the length  $P = P \left( T_1 - T_0 \right) P$ 

When the elements have the length 1 the bending that each branch under oes under the action of the a temperature gradient  $(T_1 - T_0)/1$  will have the radius of curvature

$$R = \frac{P}{AP} l = \frac{1}{p(T_i - T_o)} l$$

\* See Fig. 4 on page 29

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For instance, for  $p = 2 \times 10^{-5}$  per degree C,  $T_1 - T_2 = 300$  and Q = 0.6 cluem we find R = 100 cm.

Due to this bending a formerly plane surface of the hot soldered joint that is in close contact with an edge will travel along this edge by a segment

$$\Delta \ell = \frac{P^2}{2R} = P^2 \frac{P(T_1 - T_0)}{2\ell}$$

With the above values and a cross section of the branch of  $\rho^2 = 10000$  MKE second edge will deviate from the plane by  $\Delta L = 0.5$  cm; when the median line of the cross-sectional plane is fixed, the MKE edges MK to the right and left of it will deviate by 2.5 millimeters.

If the free bending of the battery is impeded, however, the stress may cause its destruction or, at least, the formation of cracks. The stress is the more dangerous for a given temperature difference  $T_1$  -  $T_2$ , the smaller is X and the greater is P.

Heretofore we **x** have assumed that our thermocouple was made of semiconductors with a p-type conduction in one branch and as **i**-type conduction in the other. Yet, if free electrons with the concentration  $N_-$  and the mobility  $U_+$  are present simultaneously with holes with the concentration  $N_+$  and the **makk** mobility  $U_+$  Eq. 2: must be substituted by

$$\alpha = \frac{K}{\sigma} \left\{ N_{-} U_{-} \left[ A + log_{e} \frac{2(2\pi m^{*} kT)^{\frac{3}{2}}}{h^{\frac{3}{3}}} - log_{e} N_{-} \right] - N_{+} U_{+} \left[ A + log_{e} \frac{2(2\pi m^{*} kT)^{\frac{3}{2}}}{h^{\frac{3}{3}}} - log_{e} N_{+} \right] \right\}$$

$$= N_{+} U_{+} \left[ A + log_{e} \frac{2(2\pi m^{*} kT)^{\frac{3}{2}}}{h^{\frac{3}{3}}} - log_{e} N_{+} \right] \right\}$$
and if also  $m_{+}^{*} = m^{*} = m^{*}$  then one oblines for the Thermal force 
$$\alpha = \frac{K}{\sigma} \left\{ (N_{-} U_{-} - N_{+} U_{+}) \left[ A + log_{e} \frac{2(2\pi m^{*} kT)^{\frac{3}{2}}}{h^{\frac{3}{3}} N} \right] \right\}$$

For  $N_+ U_+$  there is  $\alpha = 0$ ; in general, semiconductors with a mixed mechanism of conduction have much smaller values of  $\alpha$  than do h-type conduction semiconductors with charge carriers of uniforms sign. Semiconductors with a very great radio  $\frac{1}{2}U_+$  form an exception. For instance, in InSb this ratio is greater than 80. The forbidden zone must not be too wide in such intrinsic semiconductors in order that sufficiently high concentrations n occur.

Until now we have not considered the Thomson heat that is produced or consumed in the

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two branches by the current because of the temperature gradient  $(\tau_i - \tau_o)/\varrho$ 

If the maximum condition for  $\propto^2 \mathcal{O}$  is fulfilled in all parts of the circuit and  $\mathcal{A}$  there has the  $\mathbf{x}$  constant value  $\pm$  172 microvolts per degree, the Thomson coefficient  $\mathbf{v} = \mathbf{o}$  and, hence, the Thomson heat disappears. If this condition is not fulfilled and  $\mathbf{v} \neq \mathbf{o}$  the effect of the Thomson heat  $\mathbf{v} = \mathbf{v} = \mathbf{v}$  causes a cahnge of  $\mathbf{v} = \mathbf{v}$  at the hot soldered joint and we must put:

 $\bar{\alpha} = \frac{\alpha_1 + \alpha_0}{2}$ 

Notical action is required as to the values of the magnitudes  $\sim$  and  $\rho$  in  $\varepsilon_{ij}$  30 when the temperature T is varied, as they are functions of the temperature obeying the relationship.

onship.  $\chi p = \frac{1}{T_1 - T_0} \int_0^T \chi p \, dT$ 

Upon transition from  $T_0 = 300\%$  to  $T_1 = 600\%$  we have an variation of % by about the factor 2 and of % by a factor 4 to 5.

is not the mean value of  $\chi$ , but the mean value of its reciprocal, the mean heat resistance  $\chi$  must be taken that is increased in direct proportion with the temperature:

$$\bar{\chi} = \frac{2}{\frac{1}{x_0} + \frac{1}{x_1}}$$

It would be erroneous to assume that  $\times$  was identical with the value  $\times$ , at the hot end with the reasoning that we are only interested in the heat loss caused by heat conduction at the hot soldered joints of the thermocouple. When  $\times$  is a function of the temperature, the temperature gradient at this hot had is not equal to  $(7, -7_0/\mathcal{Q})$ . In the steady state the temperature gradient in the branches of the thermocouple will be such that

$$\chi$$
,  $\left(\frac{\partial T}{\partial x}\right)_{T=T_{i}} = \chi \frac{T_{i}-T_{o}}{l!}$ 

 $\times$  being given by Exx. Eq. (55).

With regard to the mean specific resistance be must, in order to determine the value  $\rho$  occurring in the formulas for Z and  $\eta$ , x know the temperature dependency of X, and the distribution of temperature along the bar. This distribution of temperature is a

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consequence of the temperature dependency of the thermal conductivity  $\times$  and/or its reciprocal  $/\chi$ . As  $/\chi \sim 7$  the distribution of temperature along a cylindrical bar can be described by the formulas:

$$\frac{dT}{T} = Cdx$$
,  $T = T$ ,  $e^{(x)}$ ,  $C = \frac{1}{2} \log \frac{T_0}{T}$ ,

wherein x the distance from the hot soldered joint.

When, as in most semiconductors,  $\rho(\tau)$  can be described by the formula  $\rho(\tau) = coust$ .

$$P = \frac{\int P dx}{g} = \frac{\int P(T) \frac{dx}{dT} dT}{g} = \frac{const}{Cl} \int \frac{T}{T} dT = \frac{const}{Cl} \int \frac{T}{T} dT.$$

and in the general case for an arbitrary  $\rho$   $(\top)$ 

$$\bar{p} = \frac{1}{Ck} \int_{-\infty}^{T_{i}} p(\tau) + d\tau$$

In  $E_q(2)$  (Ch. p(-1)) is expressed by the three magnitudes p(-1) and n. It has been proved by experiments that the concentration or can be varied to a great extent by the introduction of foreign substances into a semiconductor or by deviations from the precise stoiches metric composition of the basic lattice without any noticeable concomitant change of p(-1).

Foreign substances do not only change the concentration but they may also change the sign of the carriers. When the excess atoms or foreign atoms enter into the lattice in an ionized condition they give off electrons to the conduction band, producin notype conduction. P-type conduction originates when the foreign atoms attract electrons from the valency band. For instance, in PbS k notype conduction is produced by an excess of lead and potype conduction by an excess of sulfur; in either case the carrier concentration is increased. In the semiconducting Mg\_Sb\_ an excess of magnesium produces notype conduction, an excess of antimony produces potype conduction while the electric conductivity is increased from /0 to 0.1 and/er 1,000 per ohm and centimeter. In cuprous oxide Cu\_O excess of oxygen or which is the same - lack of copper increases the potype conductivity from /0 up to /0 classification

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In all these instances atoms with a low  $\dot{x}\dot{x}$  ionization potential which can readily be deprived of their electrons in a vacuum (e.g., Mg, Pb) also give off their electrons in the crystal thus increasing the concentration of the free electrons. The atoms of electronegative elements such as 0 and S that readily form negative ions when in gaseous state z become the source of a p-type conduction. It can be assumed that ionic forces excel in these types of lattices.

There also exist semiconductors, however, in which the electric conductivity is increased by an excess of any component in that only carriers of one kind characteristic for the respective ENDERGREE substance are produced. Among these semiconductors we have ZnSb in which the p-type conductivity is increased by an excess of zinc as well as of antimony; the sign of the carriers remains unchanged. There are ENDER numerous semiconductors in which, as in ZnSb, the sign of the carriers remains unchanged irrespective of which EXE substances EXE are ENDERGREE introduced.

In semiconductors with a pure valency bond the sign of the carriers produced by a foreign substance depends on the number of valency electrons of the lattice atoms. For instance, germanium and silicon are of this kind. Here to any chemical bond between two atoms each atom must contribute one electron. When an atom of the basic lattice is substituted by an atom of a different chemical nature, the latter must contribute to the lattice bond as many electrons as did the other atom. In case the foreign atom contains more valency electrons than are required to this end, the excess electrons go into the conduction band. In case there are not enough valency electrons, they are supplemented from the valency band leaving a number of holes there.

Ge and Si each have from form valency electrons per atom that saturate the mx valency bands with the contiguous atoms. Hence, the elements of the first, second and third groups of the periodic table, which do not have enough valency elections, produce p-type conduction, while the elements of the fix fifth group produce n-type conduction.

It is important to remember that this rule only holds for the substitution of a basic lattice atom by a foreign atom. For foreign m atoms located on interest interstitial positions and there causing local distortions of the basic lattice the sign of the result and remember that conductivity essentially depends on the electropositivity or electronegativity of the foreign atom. In these cases it can be antimax anticipated that a n-type conduction is produced by the elements of the first groups of the periodic table, while a p-type conduction is produced by the elements of the sixth and seventh groups, just as with ionic bands.

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Finally, a foreign atom may take its position in distorted regions and in vacancies that as a rule originate due to different rates of diffusion of the components. In such cases the electron mobility usually is increased, and the sign of the conduction depends on the local conditions.

The addition of foreign atoms or any diviation from the precise stoicheignetric composition of the compound also affects other properties of the semiconductor: As a m rule, the mobility of electrons and holes and the thermal conductivity are decreased. In both cases this can be ascribed to an increase in the concentration of scatter centers.

If the scatter conditions were mequal for electrons and phonoms the ratio of the mobility u to phonoms' share of the thermal conductivity would not be changed by the addition of foreign atoms. In that case we had the material  $x_{ph}/a = coustant$ .

M Negligible additions with concentrations smaller than 0.1 per cent do strongly decrease the mobility in Ge, while the phonoms' share of the thermal conductivity becomes halved, e.g., when 3 per cent of silicon are added.

The addition of various foreign substances to semiconductors in is the most important means which we have to change the properties of thes semiconductors  $\alpha$ ,  $\gamma$ , in a desired way. It must be kept in mind, however, that not only is the concentration n of free carriers increased by the addition of foreign substances, but also is the mobility u decreased to the effect that the conductivity  $\sigma$  is increased slower than is proportionax to n. It is true that the electrons' share in the thermal conductivity is increased by the addition of foreign substances just as is  $\sigma$ . Yet the phonons' share is decreased aim simultaneously. When these conditions are taken into account it is found that the maximum value of  $\alpha$  occurs with values of the thermodistrice force close to 172 microvolts/degree.

Foreign substances in semiconductors do not only affect their electron concentration, mobility and thermal conductivity with a fixed temperature, but also vary the dependency of these magnitudes relative to the temperature.

The scatter centers produced by foreign authorize substances of diminish the thermal conductivity in a semiconductor and effect a slower rate of increase of the thermal resistance with the temperature.

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These facts are in illustrated by Fig. 12 where two results of measurements of  $\chi$  are plotted, one for pure lead telluride (Curve 1), the other for the same material with ample doping (Curve 2). Once the thermal and electric conductivities of the two substances has been measured through a temperature range from -40 to 300°C, it is possible to compute  $\chi_{e/}$  with the help of the law of Wiedemann-Franz, subtract it from  $\chi$  and thus find the phonons' share  $\chi_{e/}$  of the thermal conductivity (Curves la and 2a).

while the ration of absolute temperatures is

For the doped semiconductor conditions are quite different. With the same ration of absolute temperatures we here have:

$$\frac{\chi_{ph}(50c)}{\chi_{ph}(300c)} = 1.05$$

This slight decrease of  $K \xrightarrow{\gamma_{\mu}}$  with increased temperature indicates that the scatter of the phonons by the foreign atoms (which is in dependent of the temperature) is much stronger than their scatter by thermal fluctuations (i.e., the interaction of the phonons with themselves).

The decisive factor for the electron concentration is the ionization work  $\triangle E$  of the foreign. Atoms in the respective substance or, in other words, the engergetic distance of the electrons of the foreign atom from the edge of the forbidden zone.

If the energy term of the atom electron is close to the edge of the conduction band, n-type conduction will result; if the atom produces a term that is closer to the edge of the valency band, electrons from this band will go to the foreign atoms and p-type conduction will xxxxx result. Denoting the energetic distance of the foreign atom from the edge of the band by  $\triangle E$  and the number of foreign atoms by N we have:

\* See Figure 6 ou page 3/1.

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n <sub>±</sub> =	2 N 2 (27 M* AT)3/	4 <u>DE</u> - e <sup>2</sup> RT	

The energy  $\triangle \mathcal{E}$  depends on the ionization potential of the foreign atom and on the dielectric constant of the base substances. For hydrogen-like atoms embedded in a medium with the dielectric constand the radius of the first orbit of the Bohr type

With an  $\mathcal{E}$  in the we order of magnitude of 10 or more, r is much greater than the lattice constant and - without any great error - the basic lattice can be regarded as continuous. Then we have

$$\Delta E = E_0 \frac{1}{\varepsilon^2} = \frac{13.5}{\varepsilon^2} \text{ eV}$$

Foreign atoms on interstitiary positions do as a rule produce a greater distortion of the lattice than those that are on regular positions. Their this holds especially for the region which contains the principal share of Coulomb's interaction energy of the ion with its environment. Therfore that the above formula must not always yield a correct  $\Delta \mathcal{E}$  with a constant  $\mathcal{E}$ , in case the foreign atoms are on interstitiary positions.

The temperature dependency of the electronic share of the thermal conductivity  $\lambda_{el}$  is described by the law of Wiedernann-Franz:

When  $\sigma$  increases with the temperature (as usually is the case in semiconductors with a low electric conductivity),  $\tau_e$  increases more rapidly than in proportion to T.

In semiconductors with a low specific resistance as they are preferred in thermocouples with a high efficiency or remains almost constant through a wide temperature range, while the mobility u is decreased as the temperature is increased. Consequently,  $\mathcal{T}$  is decreased in proportion to the tempera ture x more rapidly than with  $\mathcal{T}^{-1}$ ; therefore in these substances  $\mathcal{T}_{e/}$  decreases in proportion to the tempera ture.

In pure materials without foreign substances the mobility is decreased as the temperature is increased in accordance with u = coust or u = coust. Consequently, with constant  $n_i \times_{e_i}$  will a be decreased with increased temperature either in proportion to i = coust.

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Under conditions as they are usually found in semiconductors thermobatteries, namely, when electrons are produced by foreign atoms, cases may occur where the foreign substance is the essential cause for he the scatter of electrons and heat waves. In comparison with the scatter by foreign atoms (which is independent of the temperature) the scatter of the heat waves by fluctuations in the Brownian movements (which is in proportion with the absolute temperature) is insignificant. Hence, in such doped semiconductors the phonons share of the thermal conductivity will vary only little with the tempera ture (see Fig. 12, Curve 2a). As has beennex mentioned earlier, the temperature dependency of the electrons share of the thermal conductority is given by the temperature dependency of the product

The scatter of elctrons by ionized foreign atoms is the stronger, the smaller is the velocity of the electrons; in non-degenera ted semi-conductors the mean electron velocity is in proportion with \( \tau^{\tau} \). In semiconductors in which the mobility is conditioned by the scatter by ionized foreign atoms (as is often at the case at low temperatures) the mobility hence does not decrease but increase as the temperature is increased. When the scatter by ionized foreign atoms predominates, this also has another significant effect on the thermoelectric properties of the semiconductor: the dependency of the free path & on the kinetic energy & in that case has the form

the constant term in  $\mathcal{E}_q(2l)$  therefore assumes the value 4, and the formula for the foreign conduction of uniform sign now reads:

$$\alpha = \pm \frac{1}{\varepsilon} \left[ 4 + \log_e \frac{2(2\pi m + kT)^{3/2}}{h^3 n} \right].$$

for the optinum value

$$\alpha = 172 \left( 1 + \frac{\chi_{e1}}{\chi_{ph}} \right) \mu V / c$$

the exempes electron concentration n must be greater than when the first term in the brackets is 2.

It is true that the mobility is decreased by the addition of a foreign substance; yet, this effect is overcompensated by the increase of the electron concentration. Hence, wh with equal  $\propto$  the electric conductivity and  $\propto^2$  or are greater: As the thermal conductivity of the phonens  $\times_{\rm ph}$  is diminished by foreign atoms, the value  $z = x^2 \sigma / x$ 

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will also be increased by the introduction of ionized foreign atoms, provided the number of ions is great enough to be the principal cause for the scatter of the electrons.

Frequently the concentration is increased to such an extent by the incorparation of a great number of foreign atoms that produce free charges of foreign atoms that produce free charges of a definite sign, that a degenerated system originates. With increased concentration of is decreased, yet in the degenerated state this decrease of 2 with an increased occurs more slowly than in the manner non-degenerated state.

In m case of degeneration the optineum we value of  $\alpha$  must be found by a graphic method using tables for the functions  $F_{\ell}(\mathcal{K}_{\ell})$ . In case of strong degeneration  $\mathcal{K}_{\ell} \geq 2$  the semiconductor can be conceived as a metal with a low concentration of carriers and . The minimum remains condition  $\mathcal{K}_{\ell} \geq 2$ 

 $\frac{1}{Z} = \frac{\chi_{ph}}{\chi^2 T} + \frac{1}{\chi^2}$ 

in the general case leads to the differential equation

$$\frac{J(\frac{1}{\sigma})}{J\chi} = \frac{2}{\chi} \left( \frac{1}{\sigma} + \frac{1}{\chi_{ph}} \right)$$

wherein 2 may assume values between  $2 \frac{k^2}{e^2} T$  and  $3.3 \frac{k^2}{e^2} T$ , depending on the degree of degeneration.

For a given ration  $x_{ph}$  the value  $x_{opt}$  can be determined with the help of a graphic representation of the relation  $x_{opt}$ .

Having put forth some considerations for the selection of materials for thermoelectric batteries let us now study a few special problems, xixemit giving numerical values.

We have seen that, upon optimum xxxxx selection of the conditions, the efficiency of a thermocouple depends on the mobility of the electrons and the thermal conductivity  $\chi_{\rho\mu}$  caused by the phonons within the interval . Naturally the entire specific conductivity  $\chi$  is greater than its electronic share  $\chi_{el}$ .

Let us assume that we had matix materialized the conditions  $\alpha = 1/2 \mu V/C$ ,  $\alpha = 4/4$  for the atomic lattice and had selected the values  $5 \times 10^{-3}$ ,  $10^{-2}$  and  $2 \times 10^{-2}$  for  $2 \times 10^{-2}$ .

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Furthermore we assume  $T_o = 300\%$ . The xx values for zand  $\eta$  resulting from these conditions are compiled in tables 3 and 4. (And Figure 2 and 3)

In table 5, we furthermore state the optimum values of the efficiency for low-temperature sources of heat  $T_0 = 373^\circ K$  as well as very-high-temperature sources of heat  $1800^\circ K$ , assuming that  $T_0 = 300^\circ K$ ,  $\times_{fh} = 10^{-2}$  and  $u = 400^\circ \text{cm}^2/\text{V}_{\text{SCC}}$  in all case.

- Here now are the specifications of two thermoelectric generators:

  1)  $T_1 = 3.70^{\circ} \text{ K}$ ,  $T_2 = 300^{\circ} \text{ K}$   $\sigma = 1600^{\circ} \text{ short cut}$   $\chi_{ph} = 2 \times 10^{\circ} \text{ K}$   $\chi_{e1} = 7.2 \times 10^{-5}$   $\chi_{e2} = 2.30 \text{ k}$   $\chi_{e3} = 2.30 \text{ k}$   $\chi_{e3} = 2.30 \text{ k}$   $\chi_{e3} = 2.30 \text{ k}$   $\chi_{e4} = 2.30 \text{ k}$

In order that  $\alpha = 230$  and for 295 microvolts/degree is attained with an electric conductivity of 5-1600 per ohm and centimeter, the mobility must be very high in these two cases. Unfortunately only a few materials are known in which such high mobility coincides with a phomons thermal conductivity below 2.40-2 watt/degree centimeter.

More consistent with the properties of actual materials are XXXXXXXX

these conditions:  
3) 
$$T_1 = 600^{\circ} \text{K}$$
,  $T_0 = 300^{\circ} \text{K}$ ,  $\sigma = 1000$ ,  $\chi_{\text{ph}} = 2 \cdot 10^{-2}$ ,  $\chi_{\text{el}} = 6.5 \cdot 10^{-3}$   
 $\alpha = 200 \, \mu \, \text{Volt/vc}$ ,  $z = 1 \cdot 10^{-3}$ ,  $\eta = 8.27$ 

In the latter case  $\alpha_{\rm opt}$  would amount to 225 microvolts/degree. With the same mobility we then have  $\sigma = 8.75$  observed,  $\alpha_{\rm opt} = 6.3 \times 10^{-3}$ ,  $\alpha_{\rm opt} = 6.3 \times 10^{-3}$ ,  $\alpha_{\rm opt} = 1.7 \times 10^{-3}$ .  $\alpha_{\rm opt} = 9.76$ 

Now let us try to formulate the conditions that are required in order that a maximum efficiency be attained. We have seen that the material must have a maximum value of  $Z = \alpha^{27}/\gamma$  up to the xx highest possible temperature Tp of the source of heat.

To this end it required that:

- 1. The phonons' share of the thermal conductivity of the semiconductors must be a minimum. It can be anticipated that this requirement is best met by substances x with a low Debye tempera ture consisting of heavy and weakly bound malecules. The value of  $\chi_{ph}$  can be additionally reduced by the introduction of a foreign substance and the formation of solid solutions, provided the foreign substances do not simultaneously diminish the electron mobility to the same extent.
- The mobility of the carriers (electrons or holes) must be a maximum while condition No. 1 is maintained. It is desirable that the mobility is not too strongly decreased by the introduction of the foreign substance that increases the electric conductivity . This condition is

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best fulfilled by atomic or molecular lattices with predominantly acoustical oscillations in the thermal spectrum. The mobility can be somewhat increased by careful annealing, possibly also by adding such foreign atoms that fill in vacancies and thus partially eliminate imperfections of the lattice.

- 3. One branch of the thermocouple must have a pure p-type conduction, the other a pure n-type conduction. Expect semiconductors should be used that have a small ionization energy and such a width of the forbidden zone that up to the temperature T, the concentration of carriers virtually is only determined by the foreign atoms. Only when they have a great ration of mobility of electrons and holes, semiconductors with a narrow forbidden zone may be x used.
- 4. The electron concentration must be such along the entire length of the thermocouple from the temperature  $T_4$  to the temperature  $T_0$  that  $\alpha = 172(1+\frac{2}{36})$  microvolts/degree in all sections with the respective temperatures. This is best accomplished by varying the doping with location or by assembling the thermocouple from various parts. In the low-temperature range the doping must be smaller than in the high-temperature range because for a given  $m^{\frac{1}{2}}$ ,  $m^{\frac{1}{2}}$  a function of the ratio
- 5. An important precondition for a material's suitability is its resistance against chemical attack, especially oxidation, and adequate mechanical strength and elasticity that prevent destruction of the thermocouple by stress.
- 6. In addition to materials for the two branches a material for the bridge joining the two branches must be found. This metal must not produce any additional electric resistance at the areas where it is in contact with the semiconductors, nor may it introduce any additional stress.

The last me tew requirements are of special significance in thermobatteries. With a thermoelective force of 172 microvolts/degree in each branch and with a temperature difference of 3000 each element generates about 0.1 volt. So, thousand elements must be connected in series for a 100-volt battery. Deformations hence must be rendered innocuous by elastic linkages between the elements of the bakery and the source of heat and/or the cooling.

S. Vacum - Thermocouples. The main reason for the poor efficiency of semiconductive therenocouples is the heat transfer a from the hot to the cold end by conduction. Jointly with the heat transfer through heat waves (phonons) the scatter of electrons in a smeiconductor and the transfer of the energy picked up by election during its free path to the lattice produce an unfavorable ration of mobility to thermal conductivity.

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Because of these viewpoints a thermocauple would be of interest which is based on the thermal emission of electrons into mx a vacum. Such generator of electric energy could consist of a series of sheets having a high temperature T, arranged in a vacuum opposite another series of parallelaxix makeria parallel sheets having a low temperature T<sub>2</sub>. The thermal enission was does so much increase with the temperature that already with a temperature differenc \(\tau\_1, -\tau\_2 > 200\) the m emission of the sheets with the temperature T<sub>2</sub> can virtually be neglected against the max emission of the hot sheets. A thermoelectric voltage is produced in this system by the difference of kinetic energies. The amperage is restricted by the space charge that occurs. This space charge is the main obstacle that must be overcome in the development of vacuum-thermogenerators.

Here the thermal conductivity of the lattice is replaced by the transports of heat via the vacuum through radiation. Yet, if one takes into account the fact that thermal emissivity is restricted to one or two atomic layers, i.e. to a surface layer about  $10^{-7}$  centimeters thick, while the emission and reflection of infrared takes place withing a law layer about  $0.2\sqrt{10^{-7}}$  centimeters thick, surface with a high emission of electrons and a low emission of light can be created.

Reflectivities up to 95 to 97 per cent can be attained which signifies an equivalent diminution of the emissivity. The detrimental heat transfer, the main reason for the losses in semiconductive thermoments couples, hence can considerably be diminished in vacuum thermogenerators.

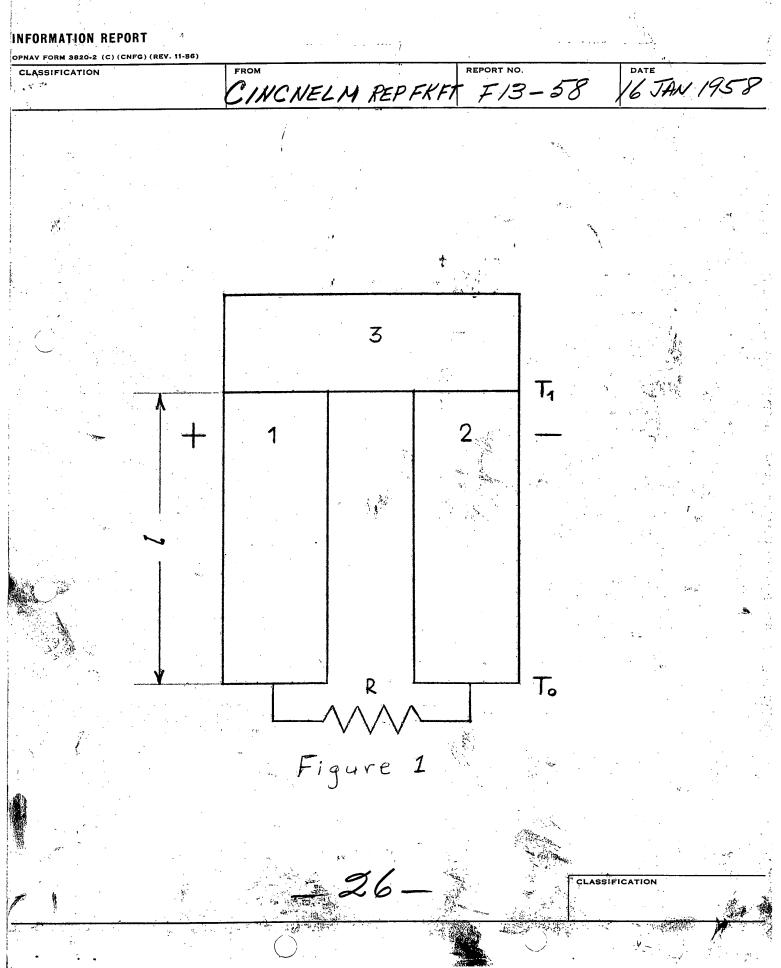
Naturally a vacuum generator can only be operated at high temperatures exceeding 900°K. It would not make sense to reduce the temperature T2 for oelow the limit at which the emission of electrons almost disappears.

With  $T_1 = 1000^{\circ} \, \text{k}$  and  $T_2 = 760^{\circ} \, \text{k}$  the thermodynamic efficiency is 30 per cent and the overall efficiency of the battery 10 ber cent. The temperature difference from  $700^{\circ} \text{K}$  to  $300^{\circ} \text{K}$  can be utilized additionally by a semiconductive thermocouphe with an efficency of 10 per cent, yielding a total efficency of 20 per cent.

Such device has a favorable energy balance, as with its help the efficiency can be greatly improved. Whether or not sources of heat of high temperature can be utilized for practical purposes by combining a semiconductive thermocouple with an electronic generator depends on the specific power of this generator, it size and its studiness; all these factors are closely related with the attainable density of the emission current.

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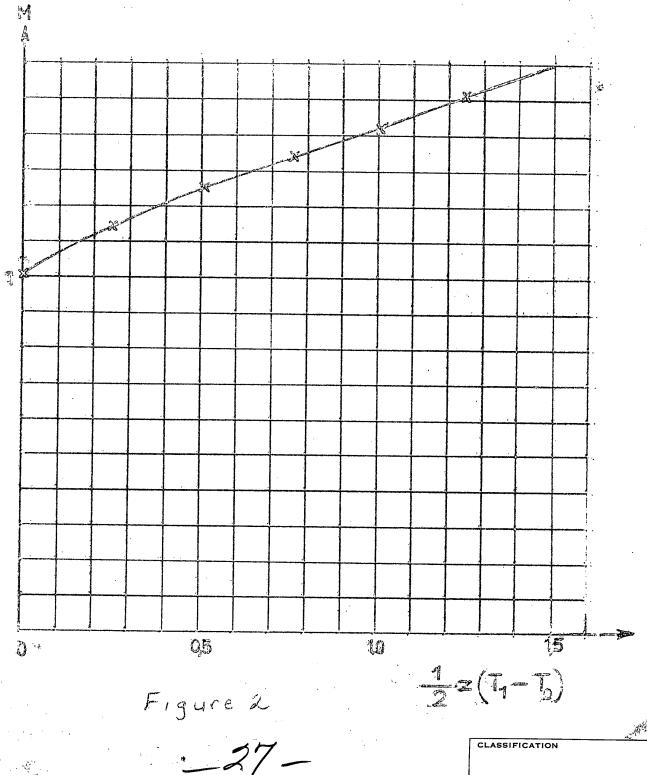


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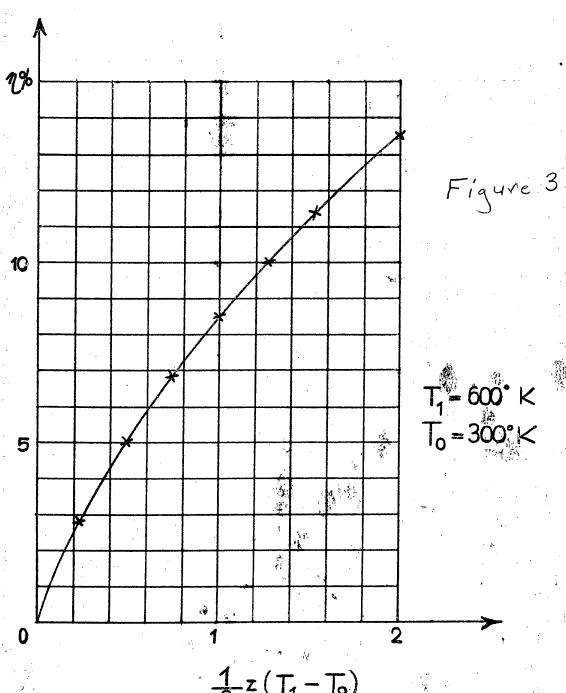
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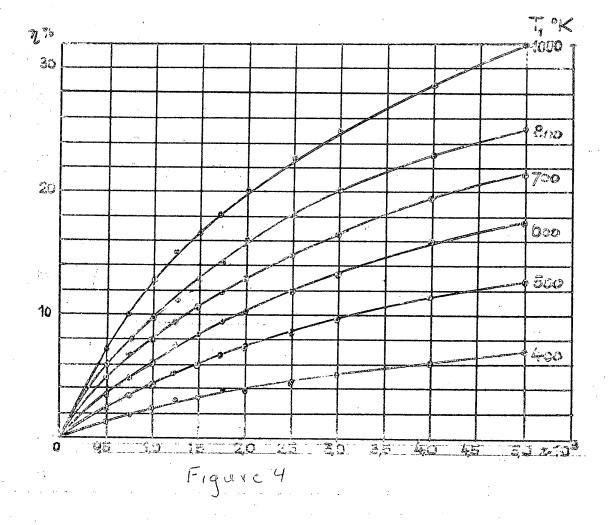


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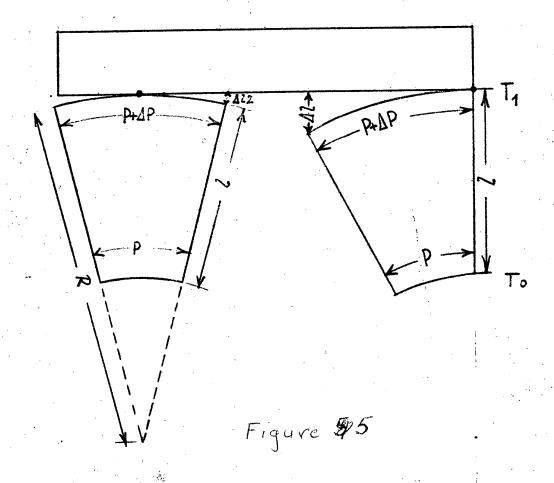
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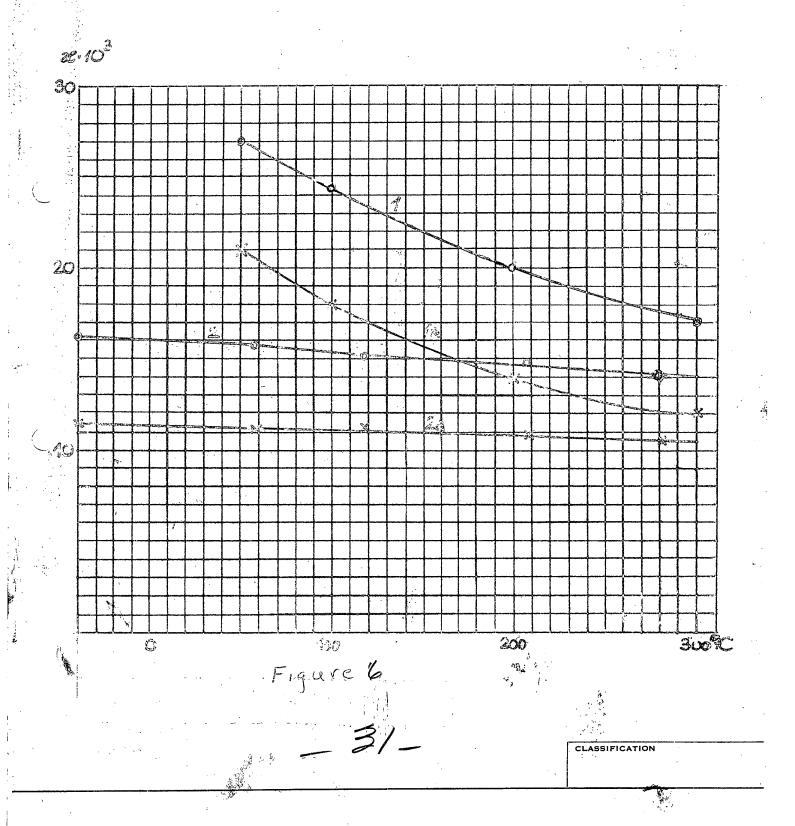
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OPNAV FORM 3820-2 (C) (CNFG) (REV. 11-86)

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16 TAN 1958

Tı° K	373	600	1000	1800
11.0pt	3.55	12.6	24.3	37.5
h thermo Ti-To	19.5	50.0 4	/ <b>/20.</b> 0	33.0
Nopt Thermodyn.	18.0	25.0	35.0	430

Figure 7.

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